

A Strategic Technology Planning Framework: A Case of Taiwan's Semiconductor Foundry Industry

Hongyi Chen, Jonathan C. Ho, and Dundar F. Kocaoglu, *Fellow, IEEE*

Abstract—The increasingly important role that technologies play in today's business success is well known. To ensure proper selection and development of the key technologies, a deliberate technology plan is needed. In this paper, a strategic technology planning framework is proposed. A hierarchical decision model and its sensitivity analysis are presented as two major steps of the framework to provide effective technology assessment and to generate technology scenarios. The hierarchical model links an organization's competitive goals and strategies in evaluating the technology alternatives' overall contributions to business success; the sensitivity analysis helps to forecast and implement possible future changes in the economic environment, industry policies, and organization strategies. With the proposed framework, organizations can start to implement their technology plans synoptically and follow up with incremental adaptations as necessary. A case study on Taiwan's semiconductor foundry industry is presented to demonstrate the model in detail.

Index Terms—Hierarchical decision model, semiconductor foundry industry, sensitivity analysis, strategic planning, technology plan.

I. INTRODUCTION

TECHNOLOGY is critical in business: It creates and maintains a firm's core competences to outperform its competitors and enables business success [7], [18], [36]. Having realized this, firms are striving to adopt technologies and put them in their business processes. Yet, technology should be properly deployed before its economic benefit can be obtained. It is the consistency or fit between technology and business operation that sets the baseline for a successful technology implementation [8], [13], [41].

To ensure long-term business survival, a firm's technology strategy should be integrated into its business strategy [7], [14] and linkage between the business goals and the technologies selected to achieve the goals should be established [14]. Therefore, a formal planning procedure for technology, which effectively facilitates the integration [7] and strives for a good match between the organization's external environment and internal structures and processes [16], should be an integral part of the business strategy. Benefits of a deliberate technology plan

include the identification of strategic opportunities and the coordination of all related activities across the organization to build on success and to avoid redundancies [15].

Although the importance of strategic technology planning is understood and different planning modes are proposed and compared in literature [5], [16], the specific planning procedures for technologies are seldom addressed in detail. In this paper, we propose a strategic technology planning framework that links an organization's technology choices with its overall mission through alignment with its competitive goals and strategies, and suggests an optimized technology portfolio. The framework starts with a comprehensive plan and is followed by periodic reevaluations and replanning, representing a combination of synoptic and adaptive planning modes. It can be applied at the industry level to guide technology policies and at the company level for technology decisions. A case study on the semiconductor foundry industry in Taiwan is presented to illustrate the application of the proposed framework. Insights regarding the strategic technology planning for Taiwan's semiconductor foundry industry are also provided.

II. LITERATURE REVIEW

A. Strategic Planning

Strategic planning has been recommended as an essential tool for managers [46]. Several researchers [17], [46], [52] compare the financial performance of companies that use formal planning with the ones that do not, and conclude that firms doing comprehensive strategic planning usually outperform others. However, the importance of a comprehensive plan is questioned by some other researchers [2], [43], and a statistical analysis showing negative relationship between comprehensiveness and performance in unstable environments is demonstrated [16]. As a result, the two types of models, *synoptic planning mode* and *adaptive planning mode* [1], [2], [16], [49], pervade the strategic planning literature [37].

In a "synoptic" strategic process, an organization establishes the overall mission, assesses the internal and external environments, evaluates alternative actions, and develops a plan to achieve the mission [1], [2], [16], [49]. While in "adaptive" planning, incremental plans are initiated in response to problems or changes, and little attempt is made to integrate the effect that such incremental change is likely to make on other parts of the organization [16], [35]. Although most literature tends to distinguish the two planning modes as polar ends of a planning continuum [37], we agree with Mintzberg [35] that few organizations can rely on a pure mode: A mixed planning should be followed in different time frames and situations to

Manuscript received January 1, 2007; revised July 1 and November 1, 2007. First published August 4, 2008; current version published January 21, 2009. Review of this manuscript was arranged by Department Editor P. Bierly III.

H. Chen is with the Department of Mechanical and Industrial Engineering, University of Minnesota Duluth, Duluth, MN 55812 USA (e-mail: honchen@d.umn.edu).

J. C. Ho is with the Department of Business Administration, Yuan Ze University, Taoyuan 330, Taiwan, R.O.C.

D. F. Kocaoglu is with the Department of Engineering and Technology Management, Portland State University, Portland, OR 97207 USA.

Color versions of one or more of the figures in this paper are available online at <http://ieeexplore.ieee.org>.

Digital Object Identifier 10.1109/TEM.2008.927815

develop organizational strategies and conduct strategic technology planning.

B. Technology Plan

As the role of technology has become increasingly critical, the importance of effective integration of technological considerations into a business strategy has been realized by more and more researchers [7], [14]. A technology road-mapping idea is proposed in [14] to help companies organize a series of workshops to discuss market drivers, product features, and technological solutions, and to link the three layers to a complete plan. In [31], the critical questions such as “what are the potential impacts of each technology on the businesses?,” “which technologies should the company invest in?,” etc., are highlighted in the technology planning process. Krajewski states that assessing the current state of technology helps a company evaluate the degrees to which the technology alternatives support the business goals, understand the influences of new technologies on its strategies, and prioritize the technology investment options [26]. Betz regards forecasting as a critical step in planning to anticipate and implement changes in the core and pacing technologies of the firm, taking into consideration the enterprise evolution, new or improved capabilities of products, production, and marketing, etc. He also notes that it is critical for technology managers to understand the impact of changes to industry policy or technology performance on business and to let the business strategy drive the technology changes [7]. The fuzzy hierarchical decision making (FHDM) is utilized in [42] to evaluate technology choices in the Indian iron-making industry. However, the paper is more focused on introducing the FHDM algorithm itself without going into details of the selection process for the evaluation criteria. Other methods such as solving the problem of incorrect customer product attribute forecasting involved in the external information gathering stage before formal technology planning starts are also proposed [51].

C. Contributions of This Paper

Though the effectiveness of different planning modes have been explored in different industries, and different ideas have been proposed regarding the development of a technology plan, the existing literature has stayed at the conceptual level without going into details of developing a comprehensive plan, linking technology choices to business goals through the alignment of organization strategies, anticipating possible future changes and creating contingency plans accordingly [35], and identifying in which direction(s) incremental adaptive changes should be made. In addition, a gap exists between synoptic and adaptive planning modes suggested by the two schools of researchers. As stated earlier, we believe that an organization should have a comprehensive plan before it starts to make adaptive changes. A good linkage between the two planning modes can be achieved by analyzing the sensitivity of the initial plan, generating “what-if” scenarios and contingency plans, and enabling rapid responses to changes. In the following section, we propose a

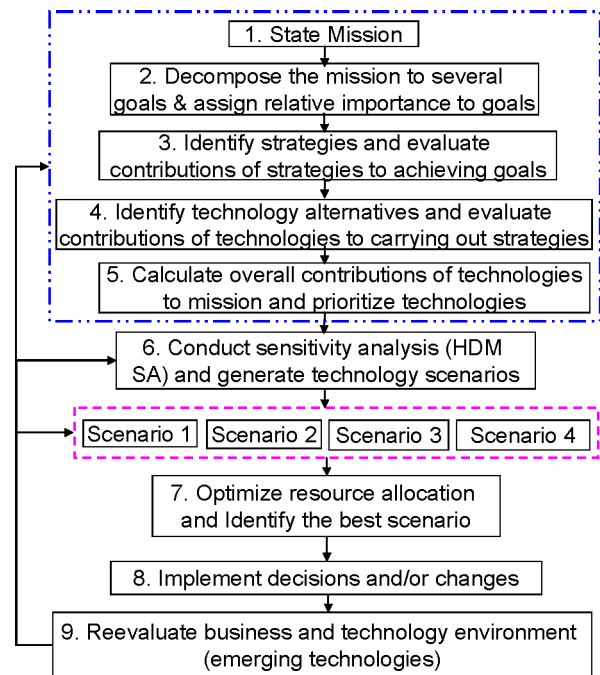


Fig. 1. Technology planning framework.

strategic technology planning framework to combine synoptic and adaptive planning modes and link the technology choices to an organization’s overall mission through alignment with goals and strategies.

III. GENERAL FRAMEWORK FOR TECHNOLOGY PLANNING

The framework contains nine steps to develop a comprehensive technology plan and forecast possible future changes and the related adaptive solutions. The steps are iterative as the organization’s environment changes. They are illustrated in detail as follows.

Steps 1 through 5: In the synoptic planning mode, alternative actions are evaluated based on their contributions to a specific, preestablished organization mission [16]. Accordingly, as depicted in Fig. 1, the first step in the proposed framework is to establish such a mission. Then, the overall mission is clarified and decomposed into more specific goals with different priorities. As noted by several researchers, the impact of technologies on strategies and competitive goals can be understood by linking the technologies to archetypes of strategies at various levels [32], [39]. It is also acknowledged that the fit between technologies and strategy patterns determines a firm’s performance [34], [48]. Therefore, strategic archetypes’ evaluation is inserted as a middle step to link the assessment of technology alternatives to organizational mission and goals.

To assess the impacts of emerging technologies on various technology strategies and competitive goals, a hierarchical technology assessment model is developed by aggregating steps one through five into hierarchical levels of interacting decision elements, as shown in Fig. 2. The competitive goals and strategies on the hierarchy are identified from literature and validated

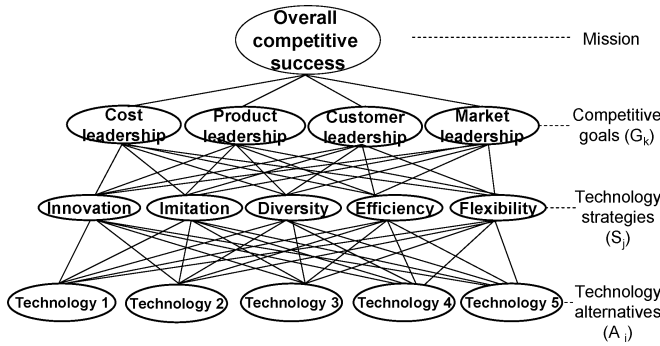


Fig. 2. Strategic hierarchical assessment model.

by experts. The model can be applied to any industry with minor changes to meet specific needs. But, it should be noted that the decision elements at each level of the hierarchy need to be preferentially independent, so that the experts are able to evaluate them against each other. In cases where synergies exist in adopting multiple technology alternatives, those alternatives should be combined and treated as a single alternative.

The model uses the AHP concept developed by Saaty [50] in dealing with multiple levels of decisions. Panel(s) of experts are formed based on their knowledge and understanding of and interests in the strategic technology plan [25]. A balanced representation of researchers and administrators with multiple perspectives should be incorporated in the process by selecting the experts from different organizations or sectors [22]. Besides, the expert panel should be large enough to assure multiple perspectives, and small enough to make the research manageable.

Based on the experts' judgments quantified by pairwise comparisons, the model first determines the relative importance of competitive goals in an industry, and then aligns technology strategies with each competitive goal. The contributions of emerging technologies to each technology strategy are evaluated and linked to the competitive goals, as well as the overall competitive success in the industry. As a result, one local contribution vector, C_k^G , the relative importance of K competitive goals, and two local contribution matrices, C_{jk}^{S-G} , relative impacts of J technology strategies on the K competitive goals, and C_{ij}^{A-S} , contributions of I technology alternatives to the J technology strategies, are obtained and aggregated to calculate the technology alternatives' global contributions to the overall mission, denoted as C_i^A . In this way, the hierarchical model helps an organization to measure the relative impacts of emerging technologies on its strategies and competitive goals. It operationalizes the concept of strategic patterns prevailing in strategic management literature [36].

Step 6: Given the most basic feature of synoptic planning, which is the emphasis on comprehensiveness in making and integrating strategic decisions [16], it is important to anticipate possible changes and develop an overall plan to meet various contingencies, especially when the organization is in a highly uncertain and fast-changing environment. Sensitivity analysis (SA) turns out to be a critical step after the initial prioritization of technology alternatives.

Therefore, the hierarchical decision model (HDM) SA algorithm, developed in [9] and [10] to test the model's robustness to changing intermediate input (the local contributions of decision elements at one level to decision elements on the next higher level), is applied.

The HDM SA algorithm contains a comprehensive set of analyses defining the allowable range of perturbations, contribution tolerance, total sensitivity coefficient (TSC), operating point sensitivity coefficient (OPSC), probability of rank changes, and the most critical decision elements when single and multiple perturbations are induced to the local contribution matrices at any level of a decision hierarchy [9], [10]. For example, Corollary 1.1 in the HDM SA algorithm presented in [10] defines the allowable range of changes to a top-level contribution value, C_k^G , which is the Contribution of the k th Goal to the mission:

Corollary 1.1: Let $P_{k^*}^G$ ($-C_{k^*}^G \leq P_{k^*}^G \leq 1 - C_{k^*}^G$) denote the perturbation induced on one of the C_k^G 's, which is $C_{k^*}^G$; the original ranking of A_r and A_{r+n} will not reverse if

$$C_r^A - C_{r+n}^A \geq P_{k^*}^G \times \left(C_{r+n, k^*}^{A-G} - C_{r, k^*}^{A-G} - \sum_{k=1, k \neq k^*}^K C_{r+n, k}^{A-G} \right. \\ \left. \times \frac{C_k^G}{\sum_{k=1, k \neq k^*}^K C_k^G} + \sum_{k=1, k \neq k^*}^K C_{r, k}^{A-G} \times \frac{C_k^G}{\sum_{k=1, k \neq k^*}^K C_k^G} \right) \quad (1)$$

The top choice will remain at the top rank if the aforesaid condition is satisfied for all $r = 1$ and $n = 1, 2, \dots, I - 1$. The rank order of all A_i 's will remain unchanged if the aforesaid condition is satisfied for all $r = 1, 2, \dots, I - 1$, and $n = 1$. [10]

"HDM" is the generic title used for the AHP and its variants developed by researchers such as Kocaoglu [25], Chu *et al.* [11], Johnson *et al.* [24], Hihn [20], Belton and Gear [6], Jensen [23], Ra [44], Barzilai and Lootsma [5], etc. It indicates the SA algorithm's independence of the various pairwise comparison scales, judgment quantification techniques, and group opinion combination methods [9], [10]. Besides testing the model's robustness, the HDM SA algorithm also generates scenarios of possible rankings for technology alternatives as the relationship among the decision elements changes [9], [10]. Conducting an HDM SA at the sixth step of the framework helps organizations to: 1) understand the impact of changes at the policy and strategy level on decisions at the operational level; 2) gain insights that do not come from the assessment results; 3) figure out possible situations and corresponding solutions in different technology scenarios; and 4) optimize their technology portfolios. As a result, when the major sources of uncertainty are eliminated as more information becomes available, managers will be more prepared and respond more quickly with better decisions.

Step 7: With the various scenarios forecasted by performing the HDM SA on the hierarchical technology assessment model, companies will have a better understanding of how each technology contributes to the different elements involved in the decision, as well as the risks associated with investing in different technologies. With all the insights gained through

step six, companies can then decide on an optimized portfolio of technology investment based on their available resources, maximizing the total overall contributions $\sum_{i=1}^I C_i$, where “ I ” is the number of technology alternatives.

Step 8: Based on the results from step seven, if an organization has enough resources to invest in the most desirable technologies, and the risks involved are acceptable, then the organization will invest in all of those technologies. On the other hand, if the organization is resource-restricted and is only able to invest in technologies that rank lower with the current evaluation, then one of three options can be chosen: 1) make the investment, and compare it with other scenarios to redefine the competitive goals and/or shift the strategies based on the HDM SA scenario to justify and maximize the benefit of such investment. Alternating strategies require change management in organizational structure, procedures, and even culture, as discussed in the strategic management literature [32], [33]; 2) If the organization is a major player in an industry or it has policy making power, it may choose to influence environmental changes to shape favorable contingencies for its investment choice. Performing HDM SA in the sixth step enables an organization to be clear about situations that favor its current strategic action. Therefore, if an organization is able to initiate endogenous changes, it may seek to shape contingencies in its favor [30]; and 3) Choose to defer the investment if the previous two choices are not possible or optimal.

Step 9: The adaptive planning should follow step eight to address and incorporate internal and external changes into the plan on a timely basis. Periodic evaluation of the business and technical environment should be carried out. Special attention needs to be given to emerging new technologies and the critical decision elements identified earlier from HDM SA. Whenever dramatic changes that cannot be analyzed by the original model and its sensitivity analysis occur, a new hierarchical model should be built and all the steps should be repeated.

It should be noted that the framework is applicable at both industry policy level and company decision level. Just as Lindblom’s “muddling” concept originates from the public policy making and gets adopted by individual firms in developing adaptive plans [27], [28], [35], the industry consortium may apply the framework to develop an industry-wide technology plan to guide the general technology investment, while the firms may use the industry-wide plan as the overall constraint and consider more specific and detailed technology alternatives to develop the company-wide plans. If necessary, an additional bottom level may be added to the hierarchical model to break down the technology alternatives into more specific techniques for firm-level applications. The major difference lies in the greater power that an industry consortium has to influence environmental changes to favor its initial decision, and access to greater resources to afford the cost of formal comprehensive analysis [35]. While applying the framework at the industry-level does not necessarily optimize the overall success of individual firms, an individual firm implementing the process can come up with strategies that differentiate itself to optimize its own success. The next section demonstrates the application of the proposed model through a case study on the technology planning for Taiwan’s semiconductor foundry industry.

IV. CASE STUDY: TECHNOLOGY PLANNING FOR TAIWAN’S SEMICONDUCTOR FOUNDRY INDUSTRY

The semiconductor foundry business provides contract integrated circuit (IC) manufacturing services to IC design companies that do not have a manufacturing facility. Equipment suppliers, materials developers, and internal process R&D are the major technology sources of the foundry industry. The industry consortium, SEMATECH, in which all the aforesaid players participate, guides the technological trends for the industry. With the proposed framework, the industry as a whole is analyzed in this paper to develop a general industry-wide strategic technology plan. The same model can be applied for individual firms by involving experts directly associated with the firm to prioritize the firm’s own competitive goals and strategies. Available resources, risk attitude, and its influencing power in the industry all affect a firm’s decision.

A. Hierarchical Technology Assessment Model

Ten experts, including foundry and foundry supplier executives, industry researchers for nonprofit organizations, and industry policy makers from government, formed the expert panel for the study. After a series of explanations, question and answers, discussions, and tests, consensus was reached for the model’s logic, definitions and measurements of the decision elements, and other related issues. Among the decision elements, competitive goals and technology strategies were first extracted from literature, and emerging technologies were identified from the SEMATECH international roadmap. They were discussed, modified, and validated by the experts. The preferential independence among elements at each level was tested to validate the model. The finalized elements in each level are summarized next.

Level I: Mission—Overall Competitive Success

The overall competitive success is a complex concept. It includes multiple measures in financial considerations, market considerations, sustainability considerations, and many others. According to Porter [40], the overall competitive success is demonstrated by attaining better return on investment (ROI) than the industry average. The same logic is followed in this research to use ROI as the indicator of the overall competitive success in Taiwan foundry industry, even though no detailed economic analysis of the different alternatives is involved.

Level II: Competitive Goals (G_k , $k = 1, 2 \dots 4$)

- 1) Cost Leadership (G_1): Keep overall costs low by reducing cycle time, increasing yield, and utilizing economy of scale.
- 2) Product Leadership (G_2): Develop cutting edge and proprietary IC process technologies. (For foundry, products are the services of IC manufacturing processes.)
- 3) Customer Leadership (G_3): Maintain intimate customer relationships to reduce lead time, to improve on-time delivery, and to provide customized processes and services.
- 4) Market Leadership (G_4): Develop new markets and strengthen the position in the existing market to influence the market and to benefit from scale of scope.

Level III: Technology Strategies ($S_j, j = 1, 2, \dots, 5$)

- 1) Technology Innovation (S_1): Use of advanced technology to develop new products for the market. This strategy leads to developing new technologies and best performance products for the market.
- 2) Technology Imitation (S_2): Quick application of a technology to product development after the product leader has proven the technology successful. This strategy leads to improving products without a heavy investment in technology development.
- 3) Technology Diversity (S_3): Use of technology to support a spectrum of products at different stages of their life cycles. This strategy leads to increasing the variety of products.
- 4) Technology Efficiency (S_4): Use of technology to improve the efficiency of production methods.
- 5) Technology Flexibility (S_5): Use of technology for rapid development of products in response to changing market demands. This strategy leads to developing products with flexibility to serve different market segments and allows for quick adjustments in production volume.

Level IV: Technology Alternatives ($A_i, i = 1, 2, \dots, 5$)

- 1) A_1 : Increasing wafer size to 300 mm and beyond (from the current 200 mm): Process technologies capable of mass production of IC devices on 300 mm wafers.
- 2) A_2 : Reducing linewidths to 90 nm and lower: Process technologies capable of mass production 90-nm-linewidth IC devices.
- 3) A_3 : High- k gate dielectrics (with k greater than 25 that replaces oxynitride $k = 7$): High- k dielectrics are materials used to decrease gate thickness and reduce electricity leakage.
- 4) A_4 : Low- k intermetallic dielectrics (with k less than 2.5 that replaces silicate glass): Low- k dielectrics are interconnecting materials among circuits of a device. Lowering interconnecting dielectrics increases the speed of IC devices.
- 5) A_5 : Factory Integration: Using technologies to coordinate and optimize various processes and tools, including equipment, material handling, facility, and other manufacturing systems.

For a four-level decision hierarchy, one vector and two matrices of local contributions between successive levels were needed. The experts' judgments were collected through judgment quantification instruments. The pairwise comparisons obtained from them were converted into a vector and two matrices: (For raw pairwise comparison data, please refer to [21])

Vector C_k^G : The relative importance of competitive goals (G_k) to overall competitive success.

Experts believed that competitive advantage is gained by successful execution of business strategies. They provided their judgment regarding the dimensions of competition in the industry. Their opinions on the relative importance of competitive goals are averaged to derive the contribution vector, as shown in Table I.

Matrix C_{jk}^{S-G} : Relative impacts of technology strategies (S_j) on competitive goals (G_k).

TABLE I
CONTRIBUTIONS OF COMPETITIVE GOALS TO OVERALL COMPETITIVE SUCCESS

C_k^G	Cost Leadership	Product leadership	Customer Leadership	Market Leadership
Overall competitive Success	0.36	0.25	0.21	0.18

TABLE II
CONTRIBUTIONS OF TECHNOLOGY STRATEGIES TO COMPETITIVE GOALS

C_{jk}^{S-G}	Innovation	Imitation	Diversity	Efficiency	Flexibility
Cost Leadership	0.02	0.11	0.14	0.43	0.29
Product leadership	0.54	0.14	0.17	0.07	0.08
Customer Leadership	0.11	0.14	0.24	0.27	0.23
Market Leadership	0.16	0.2	0.21	0.18	0.24

TABLE III
CONTRIBUTIONS OF TECHNOLOGY ALTERNATIVES TO STRATEGIES

C_{ij}^{A-S}	Increasing wafer size	Reducing line width	Hi k	Lo k	Factory Integration
Innovation	0.31	0.19	0.13	0.17	0.2
Imitation	0.29	0.24	0.11	0.17	0.18
Diversity	0.22	0.27	0.15	0.21	0.14
Efficiency	0.22	0.21	0.12	0.18	0.27
Flexibility	0.09	0.29	0.13	0.22	0.27

TABLE IV
OVERALL CONTRIBUTION VECTOR C_i^A

	Increasing wafer size	Reducing linewidth	Hi k	Lo k	Factory Integration
C_i^A	0.2196	0.235	0.132	0.193	0.2204
Ranking	(3)	(1)	(5)	(4)	(2)

Technology strategies are the decision patterns to deploy technologies in order to fulfil management objectives. In this case, these objectives are competitive goals in which the management decides to excel. Averaged judgments from the experts regarding the contributions of technology strategies to competitive goals get the contribution matrix in Table II.

Matrix C_{ij}^{A-S} : Contributions of technology alternatives (A_i) to technology strategies (S_j).

Experts determined the relative contributions of the technologies to various technology strategies, and their judgments were averaged to derive Table III.

Aggregating the local contribution matrices C_k^G , C_{jk}^{S-G} , and C_{ij}^{A-S} into an overall contribution vector, C_i^A ($C_i^A = \sum_{i=1}^I \sum_{j=1}^J \sum_{k=1}^K C_k^G C_{jk}^{S-G} C_{ij}^{A-S}$), the global contributions of technology alternatives to the overall competitive success are calculated. Technology alternatives are prioritized and ranked based on their C_i^A values, as shown in Table IV.

The results indicate that the top three technologies, "reducing linewidth," "factory integration," and "increasing wafer size," should be taken as the leading group for technology investment. Rationale behind the results is: Reducing linewidth and increasing wafer size are the two most advanced technologies in the semiconductor industry; however, increasing wafer size has a

relatively big investment risk on the foundry's side. It is estimated that a 300 mm (12 in) wafer fab may cost up to 3 billion dollars, and it is a sunk cost to foundries; the expensive mask required by reducing linewidth can be up to a half million dollars but is paid for by the foundry's customers like the fables design houses. As a result of the high capital investment requirement and the cost splitting risk-sharing scheme, increasing wafer size poses more financial risk on the foundry's side than reducing linewidth does. Factory integration is a relatively mature technology and is critical to a foundry. Compared to increasing wafer size and reducing linewidth, it requires a moderate investment in equipment to increase efficiency and flexibility of foundry operations. The risk (cost)–benefit analysis made factory integration slightly preferred to increasing wafer size, based on the experts' judgment. The fact that material technologies “hi k ” and “lo k ” gain less priorities than the top three technologies may be due to the less attention paid to material technologies at the time experts made their judgments. However, the situation may change as the industry evolves over time. The closely ranked technologies and the dynamic nature of the foundry industry call for further analysis of the model's sensitivities.

B. Sensitivity Analysis and Scenario Forecast

Based on the assessment results from the previous section, sensitivity analysis is performed to study the influences on the optimal technology portfolio when 1) changes in the economic climate of the industry cause an organization to shift its emphasis among competitive goals; 2) organization developments cause changes in technology strategies to align with altered business strategies; and 3) actual technology performance does not reach the expected level or technological advances improve the technology performance dramatically.

Specific questions being answered by performing the HDM SA in this section include: 1) What are the critical decision elements in keeping the current assessment result valid? 2) What are the probabilities of priority order changes when a certain decision element varies? 3) What is the optimal technology portfolio or the top investment choice in a most likely scenario with the least risk? and 4) What are other technology scenarios in response to future changes?

1) *Competitive-Goals Analysis*: In the assessment model, four competitive goals have been evaluated according to their relative importance to overall competitive success, which are denoted as C_k^G ($k = 1 \dots 4$). Suppose changes to industry dynamics or the economic climate demand an organization to shift its emphasis to different competitive goals; the organization needs to know whether its originally identified investment choice(s) will remain optimal. To prepare the solutions before changes happen, the HDM SA is performed to generate technology scenarios when C_k^G values vary. The most critical competitive goal worth special attention is also identified.

a) *One-way SA*: First analyzed is how variations of the C_k^G values impact the rank order of technology alternatives. A one-way SA determines the influence of changes to a single input by varying that input within its feasible range while keeping other inputs fixed at their base values [12], [45]. In our one-way

TABLE V
HDM SA AT COMPETITIVE GOALS LEVEL TO PRESERVE THE RANKING OF THE TOP A_i

	C_1^G (cost)	C_2^G (product)	C_3^G (customer)	C_4^G (market)
Base values	0.36	0.25	0.21	0.18
Allowable ranges of perturbations	[-0.285, 0.64]	[-0.25, 0.177]	[-0.21, 0.79]	[-0.18, 0.82]
Tolerance	[0.075, 1]	[0, 0.427]	[0, 1]	[0, 1]
Prob. of rank changes	7.5%	57.3%	0%	0%

SA analysis, when one contribution value changes, the other related ones will be changed according to their original ratio scale relationships, so that the new contributions still sum up to one [9], [10].

Based on Corollary 1.1 presented in [10] and cited earlier in Section III, different sensitivity indicators are calculated and summarized in Table V to deal with the situation when only the top-ranked technology is concerned. “Base value” is the value assigned to the corresponding C_k^G based on experts' pairwise comparisons. “Allowable range of perturbations” determines the thresholds of changes to C_k^G values without changing the rank order of technology alternatives, and “tolerance” is the range in which C_k^G value can change without altering the rank order of technology alternatives. “Prob. of rank changes” indicates the probability that technology alternatives' original ranking will be changed when the corresponding C_k^G , assumed to be a random variable that distributed uniformly between zero and one, changes within its feasible range (0, 1). Based on the uniformity assumption, this probability is the tolerance of C_k^G divided by the feasible range's length. These definitions are the same for SA at other levels of the hierarchy.

When limited resources restrict an organization to focus on only one emerging technology, the technology manager is mostly concerned with how robust the current top-ranked technology (“reducing linewidth” in this case) is at its current rank when the relative importance of competitive goals shifts. As we can see from Table V, “reducing linewidth” technology is very robust at its current top rank. It will not be replaced unless the relative importance of product leadership to overall success increases above 0.427. Changes to the relative importance of the other three competitive goals hardly affect the top-ranked technology: the probabilities of top choice being replaced by other technologies are 7.5%, 0, and 0 in each case. This also makes “product leadership” the most critical competitive goal in keeping “reducing linewidth” as the top choice.

In other situations, such as when the top choices are close in their scores, or when an organization has formed its technology portfolio based on the current priority order, to keep such choices optimal, the rank orders of all the technology alternatives need to be looked at. Results of the analysis on the ranking of all technology alternatives, shown in Table VI, reveal that “product leadership (G_2)” is the most critical competitive goal in this situation as well: its contribution value C_2^G has the smallest allowable change (0.008) and the second shortest tolerance (0.258) to keep the current technology ranking unchanged.

An in-depth investigation of how and under what conditions the rank of each technology alternative will change generated

TABLE VI
HDM SA AT COMPETITIVE GOALS LEVEL TO PRESERVE THE RANKING OF ALL A_i

	C_1^G (cost)	C_2^G (product)	C_3^G (customer)	C_4^G (market)
Base values	0.36	0.25	0.21	0.18
Allowable ranges of perturbations	[-0.01, 0.466]	[-0.25, 0.008]	[-0.069, 0.79]	[-0.18, 0.82]
Tolerance (C_k^G)	[0.35, 0.826]	[0, 0.258]	[0.141, 1]	[0, 1]
Prob. of rank changes	52.4%	74.2%	14.1%	0%

TABLE VII
SCENARIOS OF TECHNOLOGY ALTERNATIVES' RANKING REGARDING DIFFERENT C_k^G VALUES

		Increasing wafer size	Reducing linewidth	Hi k	Lo k	Factory Integration	Rank reverse
C_1^G (cost)	[0, 0.0751]	(1)	(2)	(5)	(4)	(3)	(1, 3)
	[0.0752, 0.349]	(2)	(1)	(5)	(4)	(3)	(2, 3)
	[0.35, 0.825]	(3)	(1)	(5)	(4)	(2)	no
C_2^G (product)	[0, 0.2584]	(3)	(1)	(5)	(4)	(2)	no
	[0.2585, 0.426]	(2)	(1)	(5)	(4)	(3)	(2, 3)
	[0.427, 1]	(1)	(2)	(5)	(4)	(3)	(1, 3)
C_3^G (customer)	[0, 0.141]	(2)	(1)	(5)	(4)	(3)	(2, 3)
	[0.142, 1]	(3)	(1)	(5)	(4)	(2)	no
C_4^G (market)	[0, 1]	(3)	(1)	(5)	(4)	(2)	no

the following technology ranking scenarios in Table VII. The technology alternatives are ranked from one to five, as shown by the bold numbers in the parentheses, when the corresponding C_k^G value changes from one range to another (the brackets in the second column indicate those ranges). In each scenario, the pair of technology alternatives whose original rank order will be changed is listed in the last column of Table VII.

From Table VII, we can see that the current top choice, “reducing linewidth” technology, is very robust to changes that occur to customer leadership and market leadership: no matter how the relative importance of these two goals change, “reducing linewidth” remains to be the top technology choice. “Reducing linewidth” dominates “factory integration” in all scenarios. This means that when an organization only has enough resources to invest in one of these two technologies, “reducing linewidth” should always be selected. “Hi- k dielectrics” and “Lo- k dielectrics” technologies are dominated by other technologies except in one case when “increasing wafer size” drops to the fourth rank.

“Increasing wafer size” gets some chances to become the top technology choice when “product leadership” is emphasized or “cost leadership” is deemphasized to certain degrees. However, its ranking is unstable and sensitive to variations of the competitive goals, especially the cost leadership. Investing in this technology represents a relatively risky approach.

In the semiconductor foundry industry, return on investment highly depends on the equipment utilization rate, and thus is subject to volatile market demands. To better utilize costly equipment investments during low seasons, foundries may shift their emphasis to cost leadership. According to Table VII, if the relative importance of cost leadership to overall success goes up, “reducing linewidth” and “factory integration” should be the top two technology choices. Contrasting to industry low seasons, when production capacity is short, cost leadership may be considered less important; in which case “increasing wafer size” will become the second, or even the top-ranked technology for

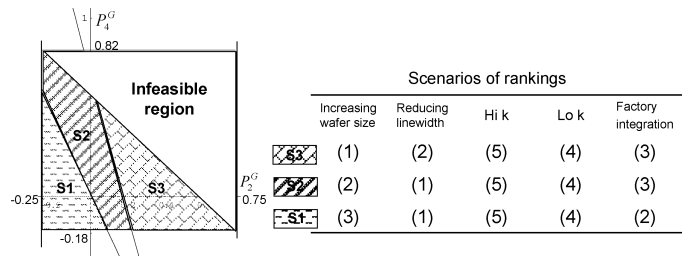


Fig. 3. Two-way SA on C_2^G and C_4^G .

Taiwan’s semiconductor industry to develop. The SA result also indicates that if there is more than a 17.7% shift of emphasis to product leadership, then “increasing wafer size” technology should be the top technology to be developed.

b) *Two-way SA (two changes)*: Among the competitive goals, product leadership (G_2) and market leadership (G_4) represent engineering perspective and market perspective. As the product performance changes rapidly, marketing continues to be a dynamic activity in the high-tech industry [7]. Improvements in technologies within and around the product system will advance the product performance and growth of the market [7]. To forecast and incorporate such progress, a two-way SA is performed accordingly to analyze simultaneous changes to the relative importance of G_2 and G_4 .

Theorem 1 of the HDM SA algorithm presented in [10] deals with multiple simultaneous changes in the top-level contribution vector. Based on the theorem, a 2-D allowable region is identified for perturbations induced on C_2^G and C_4^G in order to keep the current ranking of alternatives. (Due to limited space, the related theorems and corollaries in the HDM SA algorithm will not be quoted. Interested readers please refer to [9] or [10].)

As shown in Fig. 3, two lines intersect the feasible region and separate it into three parts representing three technology scenarios when two perturbations, P_2^G and P_4^G , are induced on C_2^G and C_4^G . “Feasible region” for P_2^G and P_4^G is an area in which the two values can change without causing any new C_k^G values to go below zero or above one. Therefore, the feasible area is defined by ($P_2^G \geq -0.25 = -C_2^G$, $P_4^G \geq -0.18 = -C_4^G$, $P_2^G + P_4^G \leq 0.57 = -(C_1^G + C_3^G)$), where P_2^G is represented by the x -axis and P_4^G by the y -axis in Fig. 3. Origin represents the original judgment when C_2^G and C_4^G are at their base values and P_2^G and P_4^G are zero. Bold numbers in the parentheses again represent the ranking of the technologies in each scenario.

From Fig. 3, we can tell that the ranking of “increasing wafer size” will either go up to the first or go down to the third. It is also shown that when the relative importance of product leadership is increased to a certain point, no matter how the relative importance of market leadership is shifted, “increasing wafer size” will be the top technology choice for the semiconductor foundries.

Among the three scenarios, S1 is the allowable region of perturbations introduced on C_2^G and C_4^G to preserve the original ranking of the technology alternatives: As long as the changes to the relative importance of product leadership and market leadership are within this region, the current ranking of

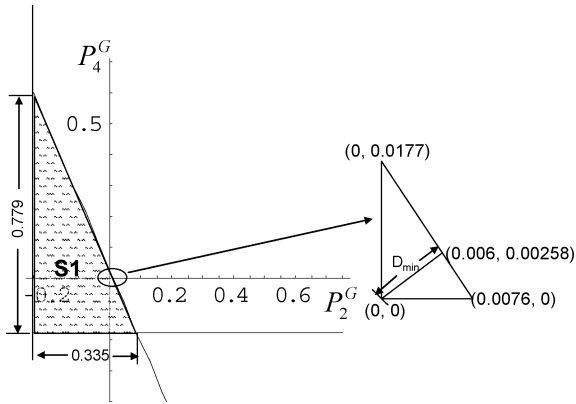


Fig. 4. Allowable region of P_2^G and P_4^G .

all the technologies will remain unchanged. The inequalities defining the sides of $S1$ are $(0.1053P_2^G + 0.0453P_4^G \leq 0.0008)$, $(-0.25 \leq P_2^G \leq 0.085)$, and $(-0.18 \leq P_4^G \leq 0.599)$.

As shown in Fig. 4, the (x, y) coordinates of important points in $S1$ can be identified through trigonometry since equations of the intersecting lines are known. Therefore, based on the HDM SA algorithm, the two criticality indicators, TSC (G_2 & G_4), which is the area of $S1$, and OPSC (G_2 & G_4), which is the shortest distance from the origin to the sides of $S1$, are calculated

$$\text{TSC}(G_2 \& G_4) = \text{Area}(S1) = 0.335 \times 0.779 \times 0.5 = 0.13$$

$$\text{OPSC}(G_2 \& G_4) = D_{\min} = \sqrt{0.006^2 + 0.00258^2} = 0.0065.$$

Since the area of the allowable region ($S1 = 0.13$) is 13% of the feasible region ($S1 + S2 + S3 = 1$), there is an 87% chance that the current ranking of technology alternatives will be changed when the relative importance of product leadership and market leadership simultaneously change in their feasible regions, based on the uniform distribution assumption.

2) *Technology-Strategies Analysis*: Along the technology planning horizon, organizations may get new or improved R&D capabilities, production capabilities, capitalization and asset capabilities, and operational capabilities as a result of enterprise evolution [7], or lose some of their research specialties due to critical personnel leaving or company market direction shifts. In addition, the fables design houses, foundries' customers, may develop new IC applications for a variety of markets. These IC chips need a wide range of manufacturing processes. Thus, new IC chips, especially those widely accepted by the market, may cause redeployment of technologies in a foundry and, as a result, change the technology strategies. In those cases, the relative impact of the technology strategies will be altered. From the perspective of synoptic planning, it is important to anticipate and incorporate the changes into the technology plans. Therefore, the HDM SA is then performed to study how variations at the technology-strategies level impact technology choices.

a) *One-way SA*: Based on [10, Corollary 2.1], the tolerance of C_{jk}^{S-G} , the relative impact of the j th technology strategy to the k th competitive goal, is calculated under two conditions:

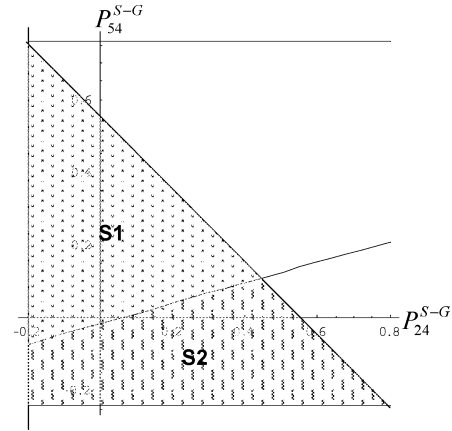


Fig. 5. Two-way SA on C_{24}^{S-G} and C_{54}^{S-G} .

1) to keep the original ranking of all technologies unchanged; and 2) to keep the current top choice the same.

The results reveal that increasing the relative impact of “innovation,” “imitation,” and “diversity” or decreasing that of “efficiency” and “flexibility” will reverse the rank order of “factory integration” and “increasing wafer size.” “Factory integration” will be the top-ranked technology when the relative impacts of “efficiency” increase. “Increasing wafer size” will become the fourth-ranked technology when “flexibility” is deemphasized. “Increasing wafer size” again has the most unstable rank when C_{jk}^{S-G} values change. “Reducing linewidth” is relatively stable at the top rank. The most influential factors at this level to keep it as the top choice are the relative impacts of different strategies, especially flexibility, to the cost leadership competitive goal.

b) *Two-way SA*: Because of the high uncertainty involved throughout the technology/product development life cycle [19], [47], especially when the technology is rapidly changing [38], disagreement may arise between experts while making judgment. Although averaging experts' judgment, the method employed in this study, is quite effective to aggregate different opinions [3], [29], it is noted that the average opinion of experts does not always yield useful results, and sometimes the reality is at one of the extremes of experts' judgments [4]. To address this issue, two-way HDM SA is applied to test the robustness of the model regarding different experts' opinions.

Among the impacts of technology strategies on competitive goals, “flexibility” to “market leadership” (C_{54}^{S-G}) and “imitation” to “market leadership” (C_{24}^{S-G}) received the greatest disagreement from the two experts who did the pairwise comparisons at this level: expert C gave 0.07 to C_{24}^{S-G} and 0.4 to C_{54}^{S-G} , while expert D gave 0.34 to C_{24}^{S-G} and 0.09 to C_{54}^{S-G} .

Performing a two-way SA on the two contribution values, two scenarios are generated, as shown in Fig. 5. $S1$ is the allowable region for perturbations induced on C_{24}^{S-G} and C_{54}^{S-G} to keep the current ranking of all the technologies unchanged, and the judgment of expert C falls in $S1$. The judgment of expert D falls in $S2$, in which the rank order of “increasing wafer size” and “factory integration” will be reversed. But in either case, the top-ranked alternative, “reducing linewidth” technology, will not be affected.

3) *Technology Performance Analysis*: As the technologies are being developed, performance may fall short or exceed expectations. Certain technologies may be progressing faster than others. In order for companies to respond quickly in the adaptive planning mode, it is helpful to anticipate different possibilities and incorporate technological advances into the technology plan, especially when the companies are in a fast-changing environment like the semiconductor industry. A good example in this case study is the rapid progress to reduce line width: when the hierarchical technology assessment model was first calibrated in the year 2004, 90-nm line width was the state of the art. However, in less than two years, the same technology has reached the point where 65 nm is applied in manufacturing and 45 nm has been achieved in research laboratories. This advance may alter the contribution matrix C_{ij}^{A-S} and generally increase the contributions of “reducing line width” technology. Therefore, the impact of technology advances on a semiconductor foundry’s technology plan is evaluated.

Based on [10, Corollary 3.1], the allowable ranges of perturbations induced on C_{ij}^{A-S} , contribution of the i th technology alternative to the j th technology strategy, are calculated. The results indicate that the smallest allowable change to C_{ij}^{A-S} to preserve the original ranking of all technologies happens on C_{14}^{A-S} , the contribution of “increasing wafer size” to “efficiency,” making “increasing wafer size” the most critical decision element at the technology-alternatives level to keep the current ranking of technologies. The contribution of “factory integration” to “flexibility” is also very critical: if it decreases by more than 0.0009, it will reverse the rank order of “increasing wafer size” and “factory integration.”

Since contribution matrix C_{ij}^{A-S} is at the bottom level of the decision hierarchy, the ranking of technologies is more sensitive to changes in this matrix. This results in much smaller threshold values of the P_{ij}^{A-S} ’s as compared to P_{jk}^{S-G} ’s and P_k^G ’s to keep the technology rankings unchanged. Therefore, in determining whether the technology portfolio is optimal along the planning horizon, the technological advancements are more critical than industry policy changes or organization strategy shifts. It is worth doing an in-depth analysis at this level to further investigate technology scenarios when each technology’s contribution to each strategy changes.

First analyzed is “reducing linewidth” technology, the current top choice that advances at the highest speed. Judging from the trend of technology advancement, the contribution of “reducing linewidth” is more likely to be increased. This will make the original ranking of all technologies to be the same, as shown in Table VIII. The rank of “reducing linewidth” changes only when its contributions decrease from the original value to a certain point, which is not likely to happen in the short future. “Hi- k dielectrics” and “Lo- k dielectrics” are again mostly dominated by other technologies.

Then, the analysis goes to “increasing wafer size” technology, which is among the top three choices but with the most unstable rank based on the previous analysis. Results reveal that only “increasing wafer size” and “reducing linewidth” get the chances to become the top choice when contributions of “increasing wafer size” to strategies change. “Factor integration” stays at rank two

TABLE VIII
RANKING OF TECHNOLOGIES WHEN CONTRIBUTIONS OF “REDUCING LINewidth” TO STRATEGIES CHANGE

		Increasing wafer size	Reducing linewidth	Hi k dielectrics	Lo k dielectrics	Factory integration
C_{11}^{A-S} 0.19 (Innovation)	[0.179, 1]	(3)	(1)	(5)	(4)	(2)
	[0.12, 0.178]	(2)	(1)	(5)	(4)	(3)
	[0.113, 0.119]	(1)	(2)	(5)	(4)	(3)
	[0, 0.112]	(1)	(3)	(5)	(4)	(2)
C_{12}^{A-S} 0.24 (Imitation)	[0.226, 1]	(3)	(1)	(5)	(4)	(2)
	[0.144, 0.225]	(2)	(1)	(5)	(4)	(3)
	[0.134, 0.143]	(1)	(2)	(4)	(4)	(3)
	[0, 0.133]	(1)	(3)	(5)	(4)	(2)
C_{13}^{A-S} 0.27 (Diversity)	[0.256, 1]	(3)	(1)	(5)	(4)	(2)
	[0.19, 0.255]	(2)	(1)	(5)	(4)	(3)
	[0.184, 0.189]	(1)	(3)	(5)	(4)	(2)
	[0.18, 0.183]	(1)	(2)	(5)	(4)	(3)
C_{14}^{A-S} 0.21 (Efficiency)	[0.07, 0.179]	(1)	(4)	(5)	(3)	(2)
	[0.17, 1]	(3)	(1)	(5)	(4)	(2)
	[0.154, 0.16]	(3)	(2)	(5)	(4)	(1)
	[0.061, 0.153]	(2)	(3)	(5)	(4)	(1)
C_{15}^{A-S} 0.29 (Flexibility)	[0, 0.06]	(2)	(4)	(5)	(3)	(1)
	[0.295, 1]	(2)	(1)	(5)	(4)	(3)
	[0.227, 0.294]	(3)	(1)	(5)	(4)	(2)
	[0.211, 0.226]	(3)	(2)	(5)	(4)	(1)
	[0.121, 0.21]	(2)	(3)	(5)	(4)	(1)
	[0, 0.12]	(2)	(4)	(5)	(3)	(1)

or three; “Hi- k dielectrics” and “Lo- k dielectrics” are mostly dominated by other technologies.

Applying the same analysis to “factor integration,” “reducing linewidth” turns out to be the top choice in most cases, but it may drop to the third rank in one scenario when “factory integration” becomes the top choice due to increases in its contributions to strategies. “Increasing wafer size” takes either second or third rank. “Lo- k dielectrics” ranks fourth in most cases and third a few times, and “Hi- k dielectrics” remains as the last choice in every scenario.

The analysis on “Hi- k dielectrics” and “Lo- k dielectrics” reveals that in most cases “reducing linewidth” ranks first with “increasing wafer size” and “factory integration” ranks second, third, or fourth in different scenarios. “Hi- k dielectrics” or “Lo- k dielectrics” can move up to the first ranking only when their contributions to the strategies are increased dramatically.

C. Final Discussion

Based on results from the hierarchical technology assessment model and its sensitivity analysis, a general conclusion can be reached: “reducing line width” is the top choice to be adopted and should be allocated with the most resources. The decision difficulty lies in the choice between “factory integration” and “increasing wafer size,” which rank the second and the third with very close overall contribution values. SA results reveal that “increasing wafer size” gets more chances to become the top choice when changes occur to local contributions; however, its rank is relatively unstable and can drop from the first to the fourth in different cases. Since the industry consortium in Taiwan has strong influencing power, it is suggested that “increasing wafer size” should be chosen, and efforts should be made to strengthen product leadership, because it is emphasized that, “reducing linewidth” and “increasing wafer size” will be the top two choices. However, suppose a risk-averse company adopted this framework and got the same model results, then

“factory integration” should be adopted instead, since it poses lower risk to the company than what “increasing wafer size” does. “Hi-*k* dielectrics” and “Lo-*k* dielectrics” are dominated by other technologies in most cases. Unless their performances can be improved dramatically, resulting in improved contributions to the technology strategies to a certain degree, they will remain as the last choices and should be allocated the least resources.

SA at the technology strategies level indicates that “factory integration” may become the top-ranked technology when the relative impacts of “efficiency” on the competitive goals are increased, and “increasing wafer size” will drop to the fourth choice when “flexibility” is deemphasized. “Reducing linewidth” is relatively insensitive to variations of the impacts of “diversity,” “flexibility,” and “imitation” except in a few situations: decreasing the relative impact of “flexibility” to “cost leadership” or increasing the relative impact of “imitation” to “cost leadership” will reverse the rank order of “increasing wafer size” and “reducing linewidth.” The same situation will happen when the “innovation” strategy is emphasized to a certain degree. Although the experts had great disagreement evaluating the relative impacts of “flexibility” and “imitation” on “market leadership,” SA results show that they do not affect the top choice, “reducing linewidth,” only the rank order of “factory integration” and “increasing wafer size,” which are very close anyway.

Factors at every level of the decision hierarchy all influence the technology choices; however, the direction and speed of technological advancement are more critical than industry policy changes and organizational strategy shifts in determining the optimal technology portfolio. Judging from current trends of technology developments, “reducing linewidth” and “increasing wafer size” are the two technologies that advance faster. Therefore, in the most likely scenario, the ranking of all the technologies is “reducing linewidth” (1), “increasing wafer size” (2), “factory integration” (3), “Lo-*k* dielectrics” (4), and “Hi-*k* dielectrics” (5). Resources should be allocated to the top three technologies, with “reducing linewidth” getting the most. Unless there is a dramatic improvement on the “Lo-*k* dielectrics” and “Hi-*k* dielectrics” technologies, these two technologies should be the lowest priority for investments.

Then, the available resource is considered in deciding how many technologies to go with for investment and development. An optimized portfolio should be constructed to achieve high overall contributions to the mission, while keeping the risks at an acceptable level. For a firm with limited resource, if it is only able to develop or acquire technologies that rank lower than others, or if it wants to justify its previous investments in those technologies, it needs to shift its emphasis among competitive goals, alter its strategies, or push for advancement of certain technologies in order to take full advantage of its investment. The changes need to be initiated in the directions indicated by the HDM SA scenarios.

Periodical reevaluation of the business and technology environment is needed to redirect organization development in a timely fashion to better utilize its technology investments. In such a periodic evaluation, “product leadership” and “innovation,” the most critical competitive goal and strategy, need spe-

cial attention since they have the greatest impact on technology choices.

In addition, new technology options frequently become available in the semiconductor foundry industry. These technologies are either planned in the SEMATECH international roadmap or emerge from outside the industry. Emergence of critical new technologies should be incorporated along the way and be evaluated together with the original technology alternatives. For example, system on a chip (SoC), which is not included in the original model, may be an additional technology alternative for evaluation in this case.

Applying [10, Corollary 3.3], the condition that needs to be satisfied in order for the current top choice, “reducing linewidth,” to remain at its rank is

$$0.97C_{61}^{A-S} + 0.75C_{62}^{A-S} + 0.97C_{63}^{A-S} + 1.33C_{64}^{A-S} + 1.17C_{65}^{A-S} \leq 1 \quad (2)$$

where C_{6j}^{A-S} ($j = 1, 2, \dots, 5$) are the contributions of the new technology alternative, A_6 , to the five technology-strategies. The conditions for the current second- and third-ranked technologies to remain unchanged are

$$1.06C_{61}^{A-S} + 0.77C_{62}^{A-S} + 0.94C_{63}^{A-S} + 1.52C_{64}^{A-S} + 1.25C_{65}^{A-S} \leq 1 \quad (3)$$

$$1.16C_{61}^{A-S} + 0.84C_{62}^{A-S} + C_{63}^{A-S} + 1.46C_{64}^{A-S} + 1.07C_{65}^{A-S} \leq 1. \quad (4)$$

From inequalities (2)–(4), we can see that C_{64}^{A-S} , the new technology’s contribution to efficiency, is a relatively more critical value in keeping the current top-, second-, and third-ranked technologies unchanged. If the new technology performs on an average level, and thus contributes to all the strategies no more than one-sixth, the current top three choices will remain the same. However, it is the combination of all C_{6j}^{A-S} values that determines whether the new technology should be adopted. With the assistance of the HDM SA, the stability of current technology choices can be roughly assessed before determining whether experts’ judgments are needed for new pairwise comparisons at the technologies level.

Technology planning is a continuous process. Updating the model is necessary to maintain its utility. Once the need for radical changes is identified from the periodic reevaluation, the organization should restructure and calibrate the hierarchical model with updated information and redo the planning process again.

V. CONCLUSION

In this paper, a framework for strategic technology planning is proposed. The first five steps of the framework are integrated into a hierarchical technology assessment model, through which an organization’s overall business success, competitive goals, strategies, and the technology choices are linked together. This helps an organization to choose technologies that contribute the most to its mission through alignment with organizational strategies. The HDM SA algorithm developed in [9] and [10]

is then applied to the assessment results to test the stability of each technology alternative at its current rank and reveal dominance relationships among the technologies. The analysis further explores the cause and effect relationships among decision elements, forecasts possible changes and corresponding solutions, and provides organizations with insights for future adaptive redirections. Conditions under which the current technology choices will remain optimal are identified to help an organization make better use of its investment in an unstable and fast-changing business environment. The analysis also benefits companies that have already invested in lower-ranked technologies or are only able to adopt technologies that do not favor their current competitive goals or strategies due to limited resources: directions in which those companies should influence the economic environment and industry policies or implement changes to their organizational strategies are highlighted.

The proposed framework offers a smooth transition between synoptic planning and adaptive planning modes. The paper extends the conceptual strategic planning literature by providing industry practitioners with a useful tool to guide them through the development of a technology plan. The procedures were illustrated in detail through a case study, in which Taiwan's foundry industry, as a single organization that owns about 80% of world market share, was analyzed. Since the whole industry was the initial user of the model, experts from a diversity of companies in Taiwan semiconductor industry formed the panel to provide judgment. However, the model is equally applicable to technology planning at the firm level. Foundries with different strategic positions may apply the model internally and generate their own strategic technology choices. More detailed technological alternatives may also be considered for firm-level application. For example, reducing linewidth, as well as other technologies can be achieved by utilizing different techniques and processes. A level of detailed techniques can be added under technology alternatives for evaluation. In that case, additional pairwise comparisons will be needed to calculate those techniques' contributions to the mission through alignment with technologies.

The model is also applicable to any other industry by restating the overall mission and decomposing it into different goals that better represent the organization's focus. Different strategies and relevant technology choices may be identified based on the industry characteristics. Though the focus of performing the HDM SA may be different, the general purpose and process will remain the same.

While the proposed framework improves an organization's ability to react quickly to foreseeable changes, it is rather limited in accommodating competitive dynamics: Impact of a company's competitors, suppliers, and customers needs to be analyzed and the organization's responses need to be treated as changes to its strategies and goals. Besides, dramatic changes that bring new competitive goals and/or strategies into consideration need to be analyzed by reconstructing the model all over again, which may increase the organization's reaction time. The sensitivity analysis addresses risks to a certain degree, but an effective method needs to be developed in future research to quantify risks and better incorporate risks in the portfolio op-

timization. In addition, the model results depend highly upon experts' judgment, thus making the quality of information gathered by the experts very critical. External information, especially input from customers, should not be neglected, and problems addressed by previous researchers such as product attribute bullwhip in technology forecasting [51] need additional attention before the formal planning process starts.

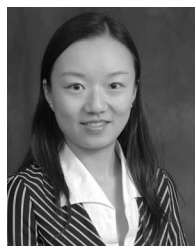
ACKNOWLEDGMENT

All the constructive feedbacks from the three anonymous reviewers and the Department Editor are highly appreciated.

REFERENCES

- [1] K. R. Andrews, *The Concept of Corporate Strategy*. Homewood, IL: Dow Jones-Irwin, 1971.
- [2] H. I. Ansoff, "The changing shape of the strategic problem," in *Strategic Management*, D. E. Schendel and C. W. Hofer, Eds. Boston: Little, Brown, 1979, pp. 23–44.
- [3] A. H. Ashton and R. H. Ashton, "Aggregating subjective forecasts: Some empirical results," *Manag. Sci.*, vol. 31, pp. 1499–1508, 1985.
- [4] R. U. Ayres, "What have we learned?," *Technol. Forecast. Soc. Change*, vol. 62, pp. 9–12, 1999.
- [5] J. Barzilai and F. A. Lootsma, "Power relations and group aggregation in the multiplicative AHP and SMART," *J. Multi-Criteria Decis. Anal.*, vol. 6, pp. 155–165, 1997.
- [6] V. Belton and T. Gear, "On a short-coming of Saaty's method of analytic hierarchies," *Omega*, vol. 11, no. 3, pp. 228–230, 1983.
- [7] F. Betz, *Managing Technological Innovation: Competitive Advantage from Change*, 2nd ed. New York: Wiley, 2003.
- [8] A. D. Chandler, *Strategy and Structure: Chapters in the History of the Industrial Enterprise*. Cambridge, MA: MIT Press, 1962.
- [9] H. Chen, "Sensitivity analysis for hierarchical decision models" Ph.D. dissertation, Portland State Univ., Portland, OR, 2007.
- [10] H. Chen and D. F. Kocaoglu, "A sensitivity analysis algorithm for hierarchical decision models," *Eur. J. Oper. Res.*, vol. 185, no. 1, pp. 266–288, 2008.
- [11] A. T. W. Chu, R. E. Kalaba, and K. Spingarn, "A comparison of two methods for determining the weights of belonging to fuzzy sets," *J. Optim. Theory Appl.*, vol. 27, no. 4, pp. 531–538, 1979.
- [12] R. T. Clemen, *Making Hard Decisions: An Introduction to Decision Analysis*. Boston, MA: PWS-Kent, 1996.
- [13] D. W. Collier, "Linking business and technology strategy," *Plan. Rev.*, Chicago, vol. 13, no. 5, pp. 28–35, 1985.
- [14] C. Farrukh, R. Phaal, and D. Probert, "Technology roadmapping: Linking technology resources into business planning," *Int. J. Technol. Manag.*, vol. 26, no. 1, pp. 2–19, 2003.
- [15] J. Fenn, A. Linden, and S. Fairchok, "Strategic technology planning: Picking the winners," *Gartner Res.*, R-20-3354, Jul. 2003.
- [16] J. W. Fredrickson and T. R. Mitchell, "Strategic decision process: Comprehensiveness and performance in an industry with an unstable environment," *Acad. Manag. J.*, vol. 27, no. 2, pp. 399–423, 1984.
- [17] J. W. Fredrickson, "The comprehensiveness of strategic decision processes: Extension, observations, future directions," *Acad. Manag. J.*, vol. 27, no. 3, pp. 445–466, 1984.
- [18] A. Fusfeld, "How to put technologies into corporate planning," *Technol. Rev.*, vol. 80, pp. 51–56, May 1978.
- [19] N. Gersdri, "An analytical approach on building a technology development envelope (TDE) for roadmapping of emerging technologies" Ph.D. dissertation, Portland State Univ., Portland, OR, 2005.
- [20] J. M. Hihn, "A hierarchical approach to decision making: Economic theory and methodology," Ph.D. dissertation, Univ. Maryland, College Park, 1980.
- [21] J. C. Ho, "Strategic evaluation of emerging technologies in the semiconductor foundry industry (special case: Taiwan semiconductor foundry industry)," Ph.D. dissertation, Portland State Univ., Portland, OR, 2004.
- [22] L. R. Hoffman, "Improving the Problem-Solving Process in Managerial Groups," in *Improving Group Decision Making in Organization*, R. A. Guzzo, Ed. New York: Academic, 1982.

- [23] R. E. Jensen, "An alternative scaling method of priorities in hierarchical structures," *J. Math. Psychol.*, vol. 28, pp. 317–332, 1984.
- [24] C. R. Johnson, W. B. Beine, and T. J. Wang, "Right–left asymmetry in an eigenvector ranking procedure," *J. Math. Psychol.*, vol. 19, pp. 61–64, 1980.
- [25] D. F. Kocaoglu, "A participative approach to program evaluation," *IEEE Trans. Eng. Manag.*, vol. EM-30, no. 3, pp. 37–44, Aug. 1983.
- [26] K. Krajewski, "Five steps to effective strategic technology initiatives," *Int. IT*, pp. 46–47, Sep. 2003.
- [27] C. E. Lindblom, "The science of muddling through," *Public Admin. Rev.*, vol. 19, pp. 79–88, 1959.
- [28] C. E. Lindblom, "Still muddling, not yet through," *Public Admin. Rev.*, vol. 39, pp. 517–526, 1979.
- [29] S. Makridakis and R. L. Winkler, "Averages of forecasts: Some empirical results," *Manag. Sci.*, vol. 29, pp. 987–996, 1983.
- [30] R. G. McGrath, "A real options logic for initiating technology positioning investments," *Acad. Manag. Rev.*, vol. 22, no. 4, pp. 974–996, 1997.
- [31] N. W. McGuaghey, "Corporate technology planning," *Ind. Manag.*, pp. 1–2, Mar./Apr. 1990.
- [32] R. E. Miles and C. C. Snow, *Organizational Strategy, Structure, and Process* (McGraw-Hill Series in Management). New York: McGraw-Hill, 1978, vol. xiii, 274 pp.
- [33] R. E. Miles and C. C. Snow, *Fit, Failure, and The Hall of Fame: How Companies Succeed or Fail*. New York: Free, vol. iv, 1994, p. 215.
- [34] A. Miller, "A taxonomy of technological settings, with related strategies and performance levels," *Strateg. Manag. J.*, vol. 9, no. 3, pp. 239–254, 1988.
- [35] H. Mintzberg, "Strategy-making in three modes," *Calif. Manag. Rev.*, vol. 16, no. 2, pp. 44–53, 1973.
- [36] H. Mintzberg, "Patterns in strategy formation," *Manag. Sci.*, vol. 24, no. 9, pp. 934–948, 1978.
- [37] V. L. Mitchell and R. W. Zmud, "Endogenous adaptation: the effects of technology position and planning mode on IT-enabled change," *Decis. Sci.*, vol. 37, no. 3, pp. 325–355, 2006.
- [38] R. T. Moriarty and T. J. Kosnik, "High-tech marketing: Concepts, continuity, and change," *Sloan Manag. Rev.*, vol. 30, no. 4, pp. 7–17, 1989.
- [39] M. E. Porter, *Competitive Strategy: Techniques for Analyzing Industries and Competitors*, 1st ed. New York: Free, 1980, vol. xxviii, 396 pp.
- [40] M. E. Porter, *Competitive Advantage: Creating and Sustaining Superior Performance*. New York: Free, Collier Macmillan, 1985, vol. xviii, 557 pp.
- [41] M. E. Porter, "What is strategy?," *Harv. Bus. Rev.*, vol. 74, no. 6, pp. 61–78, 1996.
- [42] T. R. Prabhu and K. Vizayakumar, "Technology choice using FHDM: A case of iron-making technology," *IEEE Trans. Eng. Manag.*, vol. 48, no. 2, pp. 209–222, May 2001.
- [43] J. B. Quinn, "Strategic change: Logical incrementalism," *Sloan Manag. Rev.*, vol. 20, no. 1, pp. 7–21, 1978.
- [44] J. W. Ra, "Analysis of Expert Judgments in Hierarchical Decision Process," Ph.D. dissertation, Univ. Pittsburgh, Pittsburgh, PA, 1988.
- [45] T. Reilly, "Sensitivity analysis for dependant variables," *Decis. Sci.*, vol. 31, no. 3, pp. 551–572, 2000.
- [46] L. C. Rhyne, "The relationship of strategic planning to financial performance," *Strateg. Manag. J.*, vol. 7, no. 5, pp. 423–436, 1986.
- [47] L. P. Santiago and T. G. Bifano, "Management of R&D projects under uncertainty: A multidimensional approach to managerial flexibility," *IEEE Trans. Eng. Manag.*, vol. 52, no. 2, pp. 269–280, May 2005.
- [48] Y. E. Spanos and S. Lioukas, "An examination into the causal logic of rent generation: Contrasting Porter's competitive strategy framework and the resource-based perspective," *Strateg. Manag. J.*, vol. 22, no. 10, pp. 907–934, 2001.
- [49] A. Segars and V. Grover, "Profiles of strategic information system planning," *Inf. Syst. Res.*, vol. 10, no. 3, pp. 199–233, 1999.
- [50] T. L. Saaty, *The Analytic Hierarchy Process*. New York: McGraw-Hill, 1980.
- [51] B. A. Vojak and C. A. Suarez-Nunez, "Product attribute bullwhip in the technology planning process and a methodology to reduce it," *IEEE Trans. Eng. Manag.*, vol. 51, no. 3, pp. 288–299, Aug. 2004.
- [52] D. R. Wood and R. L. LaForge, "The impact of comprehensive planning on financial performance," *Acad. Manag. J.*, vol. 22, pp. 516–526, 1979.



Hongyi Chen received the B.S. degree in power engineering economics from North China Electric Power University, Beijing, China, and the M.S. degree in engineering management and the Ph.D. degree in systems science engineering management from Portland University, Portland, OR.

Currently, she is an Assistant Professor in the Department of Mechanical and Industrial Engineering, University of Minnesota Duluth, Duluth, MN. She has served on the organizing committee for the Portland International Center for Management of Engineering and Technology (PICMET) and as a Reviewer for various conferences and journals such as the *IEEE Transactions on Engineering Management*, the *European Journal of Operational Research*, the *Technovation*, and the PICEMT. Her current research interests include strategic technology management, new product development, innovation management, and multicriteria decision making tools.

Dr. Chen is a member of The Institute for Operations Research and the Management (INFORMS), the American Society of Engineering Management, the Tau Beta Pi, and the Omega Rho.



Jonathan C. Ho was educated in Taiwan and the United States. He received the B.S. degree from Chung-Yuan Christian University, Chung Li, Taiwan, R.O.C., the M.S. degree in mechanical and aerospace engineering from the University of Missouri—Columbia, MO, and the M.S. degree in engineering management and the Ph.D. degree in systems science engineering management from Portland State University, OR.

He is currently an Assistant Professor in the Department of Business Administration, Yuan Ze University, Taoyuan, Taiwan, R.O.C. He has been a Technology Researcher in the Industry Technology Research Institute of Taiwan and a Quality Manager of Applied Materials Inc. His current research interests include technology evaluation, technological forecasting, and strategic management of technology.



Dundar F. Kocaoglu (SM'84–F'91) received the B.S.C.E. from Robert College, Istanbul, Turkey, the M.S.C.E. degree from Lehigh University, Bethlehem, PA, the M.S.I.E. and Ph.D. degrees from the University of Pittsburgh, Pittsburgh, PA.

He is currently a Professor and Chairman of the Department of Engineering and Technology Management, Portland State University, Portland, OR, and President and CEO of the Portland International Center for Management of Engineering and Technology (PICMET). He has been a Consultant to major international corporations, universities, and the United Nations. He is listed in more than a dozen Who's Who reference publications. He is the author or coauthor of more than 50 papers and is the author/editor of seven books. He has delivered more than 30 keynote speeches. His current research interests include decision theory, hierarchical decision modeling, technology management, project management, R&D management, evaluation and selection of emerging technologies, and resource optimization.

Prof. Kocaoglu is a member of various committees of the National Research Council. He has served as a Reviewer for the National Science Foundation (NSF). He has served as the Editor of the *IEEE TRANSACTIONS ON ENGINEERING MANAGEMENT* and the John Wiley Book Series on engineering and technology management. He was the recipient of the IEEE Centennial Medal, the IEEE Millennium Medal, and the Distinguished Research Mentor Award of the National Science Council of Taiwan.